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Final Technical Report (May 15, 1989 through May 15, 1992)

AFOSR Program AFOSR-89-0394

"Distributed Nonlinear Devices for Millimeter-Wave and Picosecond Pulse Generation"

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Abstract

In this program GaAs nonlinear wave propagation devices were developed for two functions; that of picosecond *impulse* compression and of broadband millimeter-wave frequency multiplication. These devices are extensions of our earlier work in shock-wave nonlinear propagation devices for picosecond *wavefront* (step-function) generation. In the course of a 3-year program, a monolithic millimeter-wave diode integrated circuit fabrication process was established (1.9 THz hyperabrupt diodes), and picosecond soliton impulse compressors and distributed frequency multipliers were first reduced to practice. Improved second-generation soliton impulse compressors subsequently fabricated generated 12.1 V (130 mA, 1.57 W peak power) impulses. While these devices generate ≈4:1 longer pulses than the shock-wave devices, the peak powers are approximately 6:1 larger, and the soliton compressors are the first high-power picosecond electronic devices.

Results with second-generation soliton distributed frequency multipliers included a doubler with 17.4 dBm peak output power at 56 GHz (24 dBm input power) and >20% bandwidth, a tripler with 12.8 dBm output power at 108 GHz (24 dBm input power) and >27% bandwidth, and a tripler with 15.2 dBm output power at 117 GHz (26.9 dBm input power). The multiplier results are important in their combined high efficiency, wide bandwidth, and high frequency of operation.

A picosecond spectroscopic system based upon the nonlinear transmission line technology was also developed under AFOSR support. The system radiates and receives 2.3 ps pulses, which are passed through experimental samples to determine their absorption-frequency characteristics. Spectroscopic measurements have been demonstrated to 250 GHz with high frequency resolution with a compact, stable, and accurate experimental apparatus.

Objectives

The program goal was to demonstrate monolithic Schottky diode GaAs circuits for efficient generation of harmonics of microwave drive signals, and for efficient generation of picosecond impulses. The method is nonlinear wave propagation on monolithic GaAs nonlinear transmission lines (NLTLs). Through generation of shock waves on NLTLs, we had previously demonstrated generation of picosecond step-functions. Modified versions of the NLTL can be used for picosecond pulse generation and frequency multiplication.

There has been a huge discrepancy between the bandwidths of electronic components used for generation of continuous-wave versus pulsed signals. Prior to our work, while electronic mixing experiments had been demonstrated at frequencies as high as 1-2 THz, the shortest pulses generated by all-electronic methods were of 20-30 ps duration. Through the use of nonlinear wave propagation principles, we have been able to apply the same devices (THz Schottky diodes) to pulse generation which had been previously used for THz mixing, and the theoretical limits to electronic pulse generation were consequently

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reduced to a few tenths of a picosecond. Thus far, experimental results with shock-wave devices have been 1-2 ps. Given the success with shock-wave devices, other nonlinear propagation phenomena (soliton propagation, distributed harmonic generation) clearly warranted exploration.

The slow development of pulse generation technologies has greatly impaired high-frequency instrumentation. There is a pressing need for instruments for characterization of millimeter-wave transistors and circuits. Picosecond pulse generators are directly applicable to millimeter-wave sampling circuits for signal and network measurements. Picosecond pulse generators also have very broad output spectrum useful for frequency multiplication and millimeter-wave spectroscopy. With a sinusoidal inputs, shock-wave devices generate sawtooth outputs whose harmonic power spectra varies as the inverse square of the harmonic order. These are inefficient high-order harmonic generators. Soliton impulse compressors generate *impulse* trains having relatively flat power spectra. These are much more efficient devices both as impulse generators (shock-wave devices require a subsequent differentiator for impulse generation) and harmonic multipliers.

Classical microwave frequency multipliers employ a single reactive or resistive nonlinear element. Resistive multipliers are inefficient, while reactive multipliers require matching networks which render them very frequency-selective. Even then, conversion efficiencies rarely exceed 50%. Optical distributed frequency multipliers (e.g. KDP crystals) often attain 90% conversion efficiency, and the analogous millimeter-wave device, the distributed frequency multiplier was therefore pursued.

Research Accomplishments

During the AFOSR program, soliton impulse compressors and distributed harmonic generators were first investigated theoretically and through computer modeling. Both the devices and the underlying diode technology were designed, diode integrated circuit fabrication processes were developed, and two successive design iterations were fabricated and tested. Following this, there was an extensive analytical effort to predict the bandwidth limits of the soliton impulse compressors, and third-generation designs were developed and laid out on masks. These last devices were not fabricated during the contract period, but will be completed shortly.

The analytical and theoretical aspects of the research program are best described in the attached publications associated with the contract. In the following paragraphs, the program is described chronologically and in terms of strategic decisions.

First Design Iteration

Impulse Compression Through Soliton Propagation

In applications where an impulse is required, the output of a shock-wave NLTL must be differentiated by a short-circuited line, with a large associated power loss. Through use of repeated splitting of solitons propagating on an NLTL, picosecond impulses can be *directly* compressed, and the resulting efficiency is much greater.

Shock waves propagate on an NLTL as a result of the balance between nonlinearity induced through the diode variable capacitance and various sources of frequency-dependent dissipation. If the diode spacings in the NLTL are greatly increased, substantial dispersion is then introduced, and the effects of high-frequency dissipation are then dominated by the high-frequency dispersion. In waveguiding systems where nonlinearity and dispersion dominate, soliton propagation is observed.

In the first part of this program, propagation of solitons on NLTLs with large diode spacings was investigated numerically by computer simulation, and the relative effects of diode dissipation and periodicity-induced dispersion identified. Impulse compression through splitting of input pulses into pairs of propagating solitons was then investigated,

and high-compression-ratio devices using multiple cascaded pulse-splitting sections were designed. Because it was determined that such structures would generate outputs with a multitude of secondary (undesired) pulses of significant amplitude, we then designed and numerically simulated exponentially tapered structures in which the pulse splitting (compression) process occurs continuously. These structures do not generate multiple secondary pulse outputs, but instead generate a (desired) compressed pulse accompanied by an long-duration pedestal, whose amplitude varies inversely with the compression rate with distance. Devices were designed for drive at 10 GHz, and with a variety of compression rates.

Because of the varying diode and line dimensions and the large number of elements, the exponentially tapered structures require automated routines (i.e. computer-generated) for mask layout. With these tools developed, investigation of exponential tapering in shock-wave NLTLs was possible, and was quickly pursued. It was learned that exponential tapering in *shock* NLTLs greatly suppresses ringing, making the NLTL useful as a precision pulse reference for picosecond metrology.

Frequency Multiplication

Shock generation on NLTLs (as viewed in the frequency domain) generates harmonics at multiples of the input frequency. By using periodicity in the NLTL to selectively introduce strong dispersion or attenuation at selected frequencies, generation of undesired harmonics can be suppressed, thereby enhancing the conversion efficiency to the single desired harmonic. Our objective is to develop harmonic multipliers with both high efficiency and broad bandwidth.

On the first design iteration, the simplest device structure, a doubler, was developed. By increasing the diode spacings relative to that of a shock-wave NLTL, the periodicity introduces a cutoff frequency which is placed in the vicinity of the third harmonic of the input frequency, thereby suppressing third-harmonic generation. Second harmonic generation was then numerically studied as a function of the number of sections in the NLTL and the input frequency relative to the Bragg frequency. Superlattice structures, in which every N^{th} diode is made larger, were also studied, but it was found that these had negligible advantage in terms of conversion efficiency. Concurrent with the frequency-domain simulations, time-domain analyses indicated that second harmonic generation was occurring through a soliton-splitting phenomenon similar to that exploited (above) for impulse compression. Simulations indicated that 50% peak conversion efficiency could be attained simultaneously with 40% relative bandwidth, a phenomenal result if realized.

Diode Design

Both the impulse compression and frequency multiplication circuits use Schottky varactor diodes as the active element. Highly nonlinear C-V curves and Terahertz cutoff frequencies are required. In addition, the impulse compression devices potentially can generate ≈15 volt pulses, and the diode reverse breakdown voltage must chosen appropriately. Modified hyperabrupt-doped diode designs were investigated with the criteria of attaining simultaneously a highly variable capacitance and a high cutoff frequency, while maintaining 15 volt reverse breakdown.

Mask Design and Process Development

Subsequent to design of the impulse compression and frequency multiplication circuits, and subsequent to the diode design, initial mask sets were laid out for the circuits, and the monolithic fabrication processes developed. In preparation for fabrication of circuits in the first design iteration, a 3-mask fabrication sequence was developed, which yielded the necessary transmission lines and 1.7 THz, 12-volt Schottky diodes with the desired capacitance-voltage characteristics.

Results

Due to GaAs materials quality difficulties, 4 successive wafers of impulse compression and frequency multiplication devices were fabricated using the first mask set. Also on this mask set were millimeter-wave sampling circuits developed under complementary NSF Presidential Young Investigator Award support. These sampling circuits were connected on-wafer to the impulse compression devices, thereby providing an on-wafer characterization tool. Measured results for the first-generation impulse compressors [1] : 4 volt impulse magnitude and 5.5 ps impulse duration at the line output. This was the first demonstration of picosecond electrical soliton compression. The results, however, were disappointing relative to the exponentially-tapered shock NLTLs on the wafer, which generated ≈1.2 ps, 4 volt step-functions. The low amplitude and long pulse duration with the soliton devices is a result of very high skin-effect losses on the long (≈2 cm) structures. The shock lines did successfully demonstrate the reduced ringing associated through exponential tapering.

Similar results were observed for the harmonic generation devices [2]. An electrooptic sampling system was implemented for device testing under the joint support of AFOSR, the NSF program, and a state of California MICRO grant. Electrooptic probing of the frequency multiplication devices clearly illustrated the soliton splitting phenomenon responsible for harmonic generation. Conversion efficiency measurement using conventional microwave instrumentation indicated 28-39 GHz bandwidth with less than 12 dB conversion loss. This was a first demonstration of the technology, but the conversion efficiency was substantially poorer than the theoretical 3 dB. As with the impulse compression devices, skin-effect losses were responsible.

<u>Second Mask Iteration</u>

Based upon the results with the first mask set, a second design iteration was pursued, which primarily addressed the high skin-effect losses encountered in both the soliton impulse compression and frequency multiplication devices.

Impulse Compression Devices

Subsequent computer modeling of the soliton compression devices indicated that observed low output resulted from excessive skin effect losses and from the diode losses, which had not been properly modeled in the first iteration. To minimize losses, soliton compression rate was studied as a function of the parameters of the inductive line sections used in the NLTL. Resulting from this study, it was found that a 2:1 reduction in the (dB) skin effect loss could be attained through use of lower-impedance line sections for the inductive interconnections. The penalty, however, is a 50% increase in die area. Simulations indicated that the diode cutoff frequency indirectly sets a limit to impulse compression: while the output impulse duration is approximately 2 times the inverse of the NLTL output Bragg frequency, if the Bragg frequency approaches within ≈10:1 of the diode cutoff frequency, the associated Bragg dispersion is no longer sufficiently dominant over the loss induced through the diode cutoff frequency, and the soliton impulse amplitude is rapidly lost. Second-generation soliton impulse compressors were therefore designed to attain 2 ps output duration (250 GHz output Bragg frequency). This slight reduction in the designed compression ratio, together with the improved interconnections, was expected to provide a 2.5:1 reduction in the (dB) skin loss. As the pulse repetition frequency is broadly tunable, a primary application of these devices will be in millimeter-wave frequency multiplication.

Frequency Multiplication Devices

As with the impulse compressors, interconnections were optimized to minimize skin effect losses, and the predicted conversion loss for frequency doublers was reduced to a

low 5 dB. Doublers for output frequencies in the range of 40, 60, and 90 GHz were designed, as were triplers with output frequencies of 75-110 GHz and 120-170 GHz, and quadruplers with outputs in the range of 130 GHz. To allow accurate conversion efficiency measurements at millimeter-wave frequencies, on-wafer sampling circuits were connected directly to the device outputs.

The above devices all used simple periodic lattices, without the sophisticated phase-matching methods originally proposed for the program. This was motivated by a the results of numerical modeling. Phase matching eliminates the loss of output power to unwanted harmonics and unconverted power in the fundamental frequency, but it was quickly determined that the dominant losses were diode and skin-effect losses. The key objective was therefore reduction of these losses.

In the case of third-harmonic and fourth-harmonic generation, a sizable fraction of the input power remains in the fundamental and lower harmonics, and selective suppression of unwanted harmonics has a greater potential impact. Addressing this, superlattice NLTL structures were investigated by analytical and numerical studies. In these structures, the capacitance of every *n*th diode is increased. This introduces a narrow frequency band (stop band) where signals cannot propagate. For a tripler, the stop band frequency is placed to suppress second harmonic generation. In the course of modeling such structures, it was found that the necessary device length for generation of the desired harmonic was greatly increased (by 2:1 or greater) with consequent large increases in the diode and skin-effect losses. Such devices were therefore abandoned in the design phase. We comment that this was a major disappointment. After extensive interactions with the millimeter-wave scientific community, we have concluded that an efficient high-order millimeter-wave frequency multiplier is of great importance. Nth-order multipliers with efficiencies of at least 1/N (or greater) would greatly increase the scope of millimeter-wave systems. As multipliers, the tapered soliton impulse compressors attain efficiencies approaching 1/N, but (once losses were considered) the superlattice multipliers were unable to surpass this performance. The distributed frequency multipliers are effective low-order multipliers.

Diode Design

Because the circuits consume large die area, and because highly nonlinear diode capacitances reduce this through increasing the compression rate, diodes with enhanced C-V nonlinearity were analyzed. To maintain diode cutoff frequency while increasing capacitive nonlinearity, the diode avalanche breakdown voltage must decrease. To eliminate this problem, we designed modified diode structures using graded or ungraded $Al_xGa_{1-x}As$ cap layers. The wider bandgap of the AlGaAs cap layer both increases the electric field required for avalanche multiplication and increases the Schottky barrier potential (reducing tunneling currents). A significant improvement in breakdown voltage was consequently expected.

Mask Design and Process Development

Mask sets for the second-generation devices were subsequently developed. The improved cell design required air-bridge interconnections and (for some circuits) silicon nitride capacitors, and approximately 3 man-months were consumed with process development. Upon completion of processing, it was found that almost none of the devices functioned as intended. After investigation (electro-optic probing, scale modeling, on-wafer tests) it was determined that high-order modes were being excited on the transmission line, particularly at the interface between the device under test and the sampling circuit used to measure its output. The mask set had to be partially revised, adding a substantial number of air-bridges for mode suppression.

Results

Following the addition of mode-suppression, the second-generation devices performed more closely to expectations. As detailed in the attached publications [5,12,16] the

distributed harmonic generation devices proved to be efficient and broadband millimeter-wave signal sources. Some waveguide-based multipliers have attained higher efficiencies due to the lower metallic losses of this media, but (to the best of our knowledge) the distributed harmonic generators attained broad bandwidth with conversion losses lower than other reported *monolithic* devices. Those operating at the highest frequencies did exhibit lower-than-expected efficiency, suggesting the presence of some unanticipated high-frequency limitation, as was also observed with the soliton compression devices.

As expected, the large reduction in skin-effect losses resulted in impulse compression devices with much larger output voltages; as high as 12.1 volts (1.57 W peak power) was observed [4]. The peak output power of the impulse was both considerably greater that the input power, and almost 10:1 larger than the impulse power from a differentiated shock-wave NLTL device. Hence the merit of the soliton compressor was clearly established with these devices. Unfortunately, the pulse durations continued to be anomalously long. Devices designed for output pulse durations of 2, 3, and 4 ps all had measured output pulse widths of almost exactly 5.0 ps.

Regarding the AlGaAs enhanced-breakdown diodes, a number of attempts were made to fabricate both the raw devices and NLTL and sampling circuits based upon them. Graded AlGaAs devices were investigated for enhanced breakdown voltage in a diode otherwise optimized for high cutoff frequency. Abrupt-junction AlGaAs/GaAs devices also show an abrupt capacitance transition and were investigated for more efficient harmonic generation. At the date of this final report, both these efforts were largely failures, primarily due to overwhelming difficulties in integrated circuit process control. The graded AlGaAs devices did show a statistically significant improvement in breakdown voltage over GaAs control devices, but both the control and experimental sample sets showed a large scatter in breakdown voltage arising from problems associated with surface damage and surface contamination arising in the process. The effort had to be abandoned. Presently, surface damage during processing has been eliminated, and the surface contamination problem arises only sporadically. Somewhat similar AlGaAs devices have been independently demonstrated by the CalTech Jet Propulsion Laboratory, and (with the AFOSR grant ended) we are again pursuing the devices under a small JPL contract.

Third Mask Iteration

Analysis, design, and mask layout for this iteration were performed during the period of the AFOSR grant, but device fabrication (now in progress) did not commence until after the program ended.

Analysis of Previous Results

With two successive attempts at soliton impulse compression devices, including several distinct variants on the second mask iteration, all devices produce pulses of almost exactly 5.0 ps duration. This was not predicted by the circuit or semiconductor device model; some unidentified high-frequency effect was increasing the pulse duration. The most probable cause was skin-effect losses, as these had known serious effects on efficiency, and yet could not be modeled correctly in time-domain computer simulation. Although computationally very demanding (at the limits of the available computers), effects of skin loss on compressed pulsewidth were studied by harmonic-balance simulations, and it was determined that skin loss was not responsible for the observed pulse width. Transmission-line radiation losses were studied and eliminated as a potential explanation, as were inductive parasitics of the device structure, and a number of other effects. Several effects were identified which might have resulted in the observed 5 ps pulsewidth. These include electron velocity saturation in the Schottky diode, the dynamics of avalanche breakdown (the observed impulse amplitudes *exceed* the diode DC avalanche breakdown voltage, but the avalanche build-up time, as best we can determine, is between 5 and 10

ps), parasitic modes at the transition into the sampling circuit used for waveform measurement, and an augmented modal dispersion effect on the soliton line.

Final Design Phase

None of the suspected effects can be modeled in circuit simulators, and hence the conclusions are tentative. The final design attempts to generate 30 volt, 2 ps pulses by addressing the suspected limits in a number of permutations. Velocity saturation effects are addressed both by using more-heavily doped diodes with thinner active layers (smaller transit times) and by use of series-connected diodes (electron velocity saturation sets a maximum rate of voltage change before the Schottky diode ceases to act as a capacitance, and series diodes doubles that maximum rate). Avalanche dynamics are addressed in some devices again by use of series diodes (with twice the total breakdown voltage) and in other devices by designs for a output voltage is smaller and hence below the steady-state breakdown voltage.

The modal dispersion effect is difficult to describe concisely. The group velocity dispersion on NLTLs is aggravated by their slow-wave properties, and the high-frequency velocity is significantly decreased. Consequently the Bragg frequency arising from the periodic network may be significantly lower than is calculated using quasi-static arguments. The net effect is that the Bragg frequency is lower than predicted, and the soliton duration is consequently proportionally increased. This effect has been indentified through full-wave (e.g. solution of Maxwell's equations in three dimensions) analysis of NLTLs recently published by 2 research groups working in the area of electromagnetic modeling. We are as yet uncertain of the magnitude of the effect, but have addressed the effect by designing some fraction of the devices with proportionally increased Bragg frequencies.

Parasitic mode excitation at the NLTL-sampling circuit interface is strongly suspected, as this caused documented problems earlier in the program. We may have only partially solved the problem on earlier attempts. On the last design phase, we have eliminated bends in transmission line connecting the soliton compressor to the sampling circuit and changes in line dimensions are made very slowly.

Finally, some fraction of the devices were designed with 4.5 THz diodes (rather than 1.7 THz), even though the higher diode cutoff frequency should only be necessary for soliton lines producing impulses of below 2 ps duration. In the event that the other undetermined high-frequency limits are indeed layout-related, these devices should produce high-amplitude impulses of below 2 ps duration.

<u>Millimeter-wave spectroscopy</u>

Concurrent with the work on soliton pulse compressors and frequency multipliers, we pursued experiments in picosecond spectroscopy, whereby a picosecond electrical transient is radiated, passed through some material under test, and detected. By Fourier analysis of the received pulse, the amplitude and phase of the material's dielectric properties can be determined. This work was performed against a background of published work: millimeter-wave spectroscopy was demonstrated some 30 years ago, and recent femtosecond transient systems using mode-locked lasers have demonstrated measurements to 1-2 THz. An NLTL-based system addresses the considerations of simplicity. It covers a broad frequency range without multiple bands of waveguide components, and eliminates the femtosecond mode-locked lasers.

As with the soliton devices, success in this experiment required two mask iterations. Both iterations used shock-wave NLTL wavefront generators and picosecond sampling circuits as pulse generators and detectors. In our first attempt, exponentially-tapered coplanar-strip transmission lines were used as the radiating and receiving antennas. In the literature, these had been described as broadband and frequency-independent. Our experiments revealed very poor antenna performance [11]. Discussions with researchers in the millimeter-wave community led to the conclusion that the exponentially-tapered antennas are in fact not frequency-independent, hence these were abandoned.

In the second mask iteration planar monolithic bowtie antennas were employed. These had shown low attenuation, good matches, and flat frequency response in scale-model experiments, and neatly integrate with the NLTL and sampling circuits. The resulting system was able to transmit and receive 2.4 ps, 270 mV pulses [6]. After investigation of various sources of measurement error in antenna systems, very accurate attenuation-phase measurements were demonstrated from 30 to 250 GHz.

List of Personell and Degrees

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1) Micheal Garth Case
Master's Degree Awarded Spring 1991
Ph. D. Expected June 1993

2) Eric Scott Caman
Master's Degree Awarded Spring 1992

3) Kathryn Abe
Master's Degree Awarded Spring 1991

Consulting and Advisory Functions

There have been no formal consulting services provided to industry or DOD laboratories regarding the technical subject matter of the AFOSR grant. The NLTL pulse generation and sampling technologies have been of significant interest to microwave instrument manufacturers, and two of these (Tektronix and Wiltron) have sent engineering and/or management personnel to UCSB to discuss the technologies and their application to commercial microwave instrumentation.

Inventions and Patent Disclosures

The general concepts of both the soliton impulse compression devices and the distributed frequency multipliers both predate the AFOSR grant, although first reduction to practice in the microwave/millimeter-wave regime was realized during the program. In the case of picosecond spectroscopy using NLTLs the experimental method is novel, but it is unclear whether there is current commercial interest. University of California patent policy discourages filing of patents without the commitment of industry, and hence patents were not filed on this technology.

Conclusions and Future Scope

Extending upon earlier work on shock-wave NLTLs, basic principles of two related devices were investigated in the AFOSR program. Following analytical work, several experimental design-and-test cycles resulted in devices with performance exceeding competitive approaches for the intended application. For both devices, however, performance was lower than expected. For the soliton impulse compressors this is being addressed with a final design iteration extending beyond the conclusion of the grant.

The program was an initial technology demonstration. Further development is being continued under several programs. Shock-wave devices with near-THz bandwidths and free-space soliton and harmonic devices are being pursued under a current AFOSR program with UCSB. The free-space devices are attempts at scalings to much higher power levels, and subpicosecond pulse widths.

A program between UCSB and Caltech JPL will explore distributed harmonic generation devices using AlGaAs/GaAs diode technology developed at JPL. Interest in the distributed harmonic generation devices has also been shown by a group at the NASA/JPL-funded Center for Space THz Technology, and effort we are trying to encourage and assist. The key issue to be addressed is more efficient generation of a desired high-order harmonic. Phase-matching strategies will be important, but only if metallic and diode losses can first be made substantially smaller.

Because of their high power, the soliton impulse compression devices are key components for picosecond switching arrays, and are an important component in a consortium proposal submitted to DARPA for 100 GB/s multiplexed fiber-optic data networks. The picosecond/millimeter-wave spectroscopy work is being continued under an AFOSR AASERT program, and we anticipated attaining bandwidths approaching 1 THz with the system.

List of Written Publications in Technical Journals

1. Michael Case, Masayuki Kamegawa, Ruai. Y. Yu, M.J.W.Rodwell, and Jeff Franklin; "Impulse Compression Using Soliton Effects in a Monolithic GaAs Circuit". Applied Physics Letters, Vol. 58, No. 2, pp. 173-175, January 14 1991.

2. Eric Carman, Kirk Giboney, Michael Case, Masayuki Kamegawa, Ruai Yu, Kathryn Abe, Mark Rodwell, and Jeff Franklin , " 28--39 GHz Distributed Harmonic Generation on a Soliton Nonlinear Transmission Line" IEEE Microwave and Guided-Wave Letters, Vol. 1, No. 2, pp. 28-31, February 1991.

3. Mark Rodwell, Masayuki Kamegawa, Ruai Yu, Michael Case, Eric Carman, and Kirk Giboney, " GaAs Nonlinear Transmission Lines for Picosecond Pulse Generation and Millimeter-Wave Sampling" IEEE Transactions on Microwave Theory and Techniques, Vol. 39, No. 7, July 1991, pp. 1194-1204.

4. Michael Case, Eric Carman, Ruai Yu, and M.J.W. Rodwell, "Picosecond Duration, Large-Amplitude Impulse Generation Using Electrical Soliton Effects" Applied Physics Letters, Vol. 60, no. 24, 15 June 1992, pp. 3019-3021.

5. Eric Carman, Micheal Case, Masayuki Kamegawa, Ruai Yu, Kirk Giboney, and M.J.W. Rodwell, "V-Band and W-Band Broadband, Monolithic Distributed Frequency Multipliers" IEEE Microwave and Guided-Wave Letters, Vol. 2, No. 6, pp. 253-254, June 1992

6. Y. Konishi, M. Kamegawa, M. Case, R. Yu, M.J.W. Rodwell, and D.B. Rutledge, "Picosecond Spectroscopy Using Monolithic GaAs Circuits", *To be published,* Applied Physics Letters, December, 1992.

Papers Presented at Conferences

7. Michael Case, Ruai. Y. Yu, Masayuki Kamegawa, Mani Sundaram, M.J.W.Rodwell, and A.C. Gosssard; "Accurate 225 GHz Sampling Circuit Implemented in a 3-Mask Process". Device Research Conference, Santa Barbara, CA, June 25-27, 1990

8. Michael Case, Masayuki Kamegawa, Ruai. Y. Yu, Kirk Giboney, M.J.W.Rodwell, J. Bowers and Jeff Franklin; "62.5 ps to 5.5 ps Soliton Compression on a Monolithic Nonlinear Transmission Line". 1990 Device Research Conference, Santa Barbara, CA, June 25-27, 1990

9. Michael Case, Eric Carman, Masayuki Kamegawa, Kirk Giboney, Ruai Yu, Kathryn Abe, Mark Rodwell, and Jeff Franklin , " Impulse Generation and Frequency Multiplication Using Soliton Effects in Monolithic GaAs Circuits" , Presented at the OSA topical meeting on Picosecond Electronics and Optoelectronics, March 13-15, Salt Lake City, Utah.

10. M. Rodwell, M. Kamegawa, M. Case, R. Yu, K. Giboney, E. Carman, J. Karin, S. Allen, and Jeff Franklin, "Nonlinear Transmission Lines and their Applications in Picosecond Optoelectronic and Electronic Measurements", 1991 Engineering Foundation Conference on High Frequency/ High Speed Optoelectronics, Palm Beach, Fla, March 18-22.

11. M. Kamegawa, Y. Konishi, M. Case, R. Yu, and M. Rodwell "Coherent Broadband Millimeter-Wave Spectroscopy Using Monolithic GaAs Circuits", Presented at the 1991 LEOS Summer Topical Meeting on Optical Millimeter-Wave Interactions, July 24-26, Newport Beach, CA.

12. Eric Carman, Micheal Case, Masayuki Kamegawa, Ruai Yu, and M.J.W. Rodwell, " V-Band and W-Band Broadband, Monolithic Distributed Frequency Multipliers" 1992 IEEE/MTT International Microwave Symposium, Albuquerque, NM, June 1-5.

13. Mark Rodwell, S. Allen, M. Kamegawa, K. Giboney, J. Karin, M. Case, R. Yu, and J.E. Bowers, "Picosecond Photodectectors Monolithically Integrated with High-Speed Sampling Circuits" Presented at the AFCEA DoD Fiber Optics Conference, 24-27 March, 1992

14. Y. Konishi, M. Kamegawa, M. Case, R. Yu, M.J.W. Rodwell, and D.B. Rutledge, "Broadband Millimeter-Wave GaAs Transmitters and Receivers Using Planar Bow-Tie Antennas", Presented at the 1991 NASA Symposium on Space TeraHertz Technology.

15. Michael Case, Eric Carman, Ruai Yu and M.J.W. Rodwell, "Picosecond Duration, Large Amplitude Impulse Generation Using Electrical Soliton Effects on Monolithic GaAs Devices" 1992 IEEE Device Research Conference, June 22-24, Boston, MA

16. Eric Carman, Michael Case, Masayuki Kamegawa, Ruai Yu, Kirk Giboney, and M.J.W. Rodwell, "Electrical Soliton Devices as >100 GHz Signal Sources" 1992 Ultrafast Phenomena VIII Conference, June 8-12, Antibes, France.

17. Mark Rodwell: "GaAs Nonlinear Transmission Lines for Picosecond and mm-Wave Applications", Invited presentation at the IEEE Second International Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits, October 7-9, Duisburg, Germany

18. Y. Konish, M. Kamegawa, M. Case, R. Yu, and M.J.W. Rodwell: "An accurate, high resolution 30-250 GHz Free-Space Vector Transmission Measurement System Using Monolithic GaAs ICs". To be presented at the 17th International Conference on Infrared and Millimeter Waves, December 14-18, 1992, Pasadena, CA.